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Radiation-resistant erbium-doped silica fibre

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***Abstract*. It is shown that the service life of erbium-doped fibres can be increased many times under conditions of an elevated radiation level by loading the fibre glass network with molecular hydrogen. Backdiffusion of hydrogen from the fibre in the process of its operation is virtually excluded for the fibre covered with a hermetic carbon coating. It is shown that this technique of fibre preparation allows one to slow down significantly degradation of the lasing properties of erbium fibres under the conditions characteristic of space applications.**

Keywords: *erbium fibre laser, molecular hydrogen, radiation resistance.*

1. Introduction

Active erbium-doped optical fibres (erbium fibres) have found wide applications in fibre amplifiers in optical communication systems [1, 2], fibre lasers [2], and superluminescent sources for fibre sensors [3], including fibreoptic gyroscopes [3, 4].

At present, the possibility is investigated to employ erbium fibres in inter-satellite and satellite – Earth optical communication systems [5] (there exists a transparency window of the atmosphere at 1.55 μm in the region of erbium fibre emission [6]) and in superluminescent sources in fibreoptic gyroscopes used aboard satellites [7]. Feasibility of these applications depends on solving the problem of radiation resistance of erbium fibres. Although the dose absorbed by fibres in space will not be so high (no more than 2 kGy during 10 years of satellite operation [7]), rare-earth-doped fibres are extremely radiation-sensitive, and an inadmissibly high radiation-induced loss (RIL) is therefore anticipated [7 – 9]. The radiation sensitivity of a fibre is enhanced not only by rare-earth doping, but also by aluminum oxide doping [9], which is required to increase solubility of a rare-earth element in silica in order to suppress its clustering. The low radiation resistance of erbium fibres calls into question their space applications.

Earlier we have demonstrated a technique to significantly enhance the radiation resistance of undoped-silica-core fibres intended for use in the nuclear industry at characteristic radiation doses of $\sim 10^6$ Gy [10 – 14]. Such fibres were manufactured in a hermetic coating (aluminum or carbon coating), and then their glass was loaded with molecular hydrogen gas at a high pressure and temperature. Under the action of ionising radiation, hydrogen atoms form chemical bonds at the sites of gamma-radiation-disrupted bonds in the glass network, thereby 'healing' radiation colour centers and, accordingly, considerably reducing the RIL. Note also that at room temperature H_2 virtually does not escape from the glass of a hermetically coated fibre: its concentration decreases by no more than several percent during a year.

The aim of this work was to investigate the applicability of the above technique to increasing the radiation resistance of an erbium fibre and to assess the gain in radiation resistance obtained in this way.

2. Experimental

A single-mode fibre with a high erbium concentration ($\sim$ 1200 ppm) and a concentration of aluminum oxide of $\sim$ 6.5 mol.% was fabricated. A fibre with such a core composition features a high absorption coefficient of the pump radiation (13 dB m^{-1} at a wavelength of 980 nm) and low clustering, which allows the creation of an efficient fibre laser using a relatively short fibre (1 m). In the drawing process, a hermetic carbon coating was applied onto the fibre [14].

Figure 1 shows schematically the experimental setup for measuring the fibre lasing efficiency. A fibre laser cavity was formed by a fibre Bragg grating spliced with the active fibre on one side and an erbium fibre end-face on the other side.

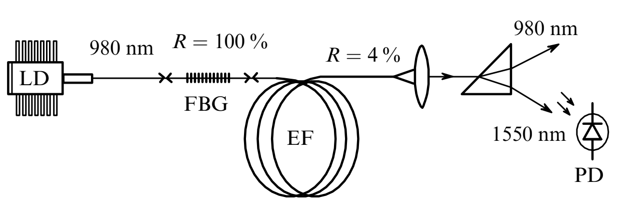

Figure 1. Scheme of the experimental setup for measuring the lasing efficiency of the erbium fibre (EF): (LD) a 980-nm semiconductor laser with a fibre pigtail; (FBG) fibre Bragg grating, (PD) photodiode.

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The grating reflectivity R was close to 100 % at the resonance wavelength of 1550 nm, and the fibre end-face reflectivity was 4 %. A single-mode semiconductor laser with a fibre pigtail was used for pumping at $\lambda_p = 980$ nm. The pump and the signal ($\lambda_s = 1550$ nm) were separated with the help of a silica prism. In all experiments, the length of the erbium fibre was the same (120 cm). The dependence of the output laser power on the input pump power was measured and the differential lasing efficiency was thus determined.

It is known that one of the negative consequences of hydrogen loading of erbium fibres is an increase in optical losses [15]. To determine the magnitude of this effect, two pieces of the fibre under study were H_2-loaded by placing them in a hydrogen atmosphere at an elevated temperature. One of the pieces was kept in hydrogen at a pressure of 5 MPa and the other – at 110 MPa. The H_2-loading of these fibres was performed during the time required to obtain the maximum H_2 concentration in the fibre glass at these pressures. The measurements showed that the differential lasing efficiency after H_2-loading at the pressure $P_{H_2} = 5$ MPa decreased only slightly (from 43 % to 40 %), whereas after H_2-loading at $P_{H_2} = 110$ MPa, the lasing efficiency decreased by half. Therefore, in the subsequent experiments on radiation resistance, only the fibre H_2-loaded at the pressure of 5 MPa was used.

The active fibre pieces – the as-drawn (H_2-free) fibre piece and the H_2-loaded fibre piece (5 MPa) – were exposed to gamma rays from a ^{60}Co source at room temperature up to a dose of 2.0 kGy at a dose rate of 0.028 Gy s^{-1}. To avoid noticeable RIL relaxation during the measurements, the optical loss spectra in the fibres were measured within one day after finishing the irradiation.

Optical loss spectra were measured again within 4 months after the irradiation, when the active properties of the fibres were also measured.

3. Results and discussion

Figure 2 shows the optical loss spectra of the as-drawn and H_2-loaded erbium fibres before and after the gamma-irradiation, and Fig. 3 shows RIL in these two fibres determined as the difference of the spectra before and after irradiation.

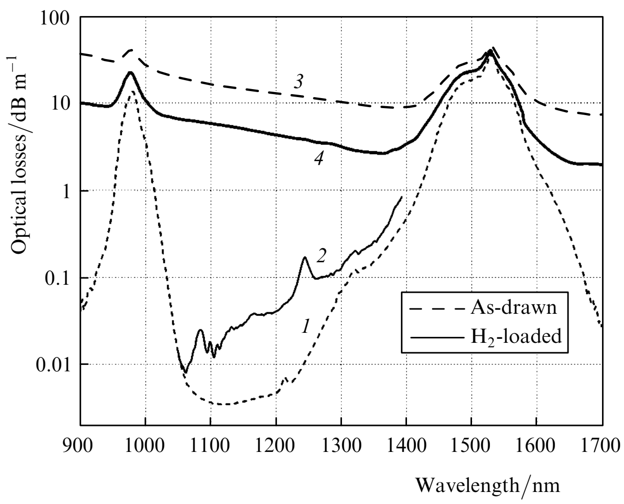

Figure 2. Optical loss spectra in the as-drawn (*1*, *3*) and H_2-loaded fibre (*2*, *4*) before (*1*, *2*) and after (*3*, *4*) the irradiation, respectively.

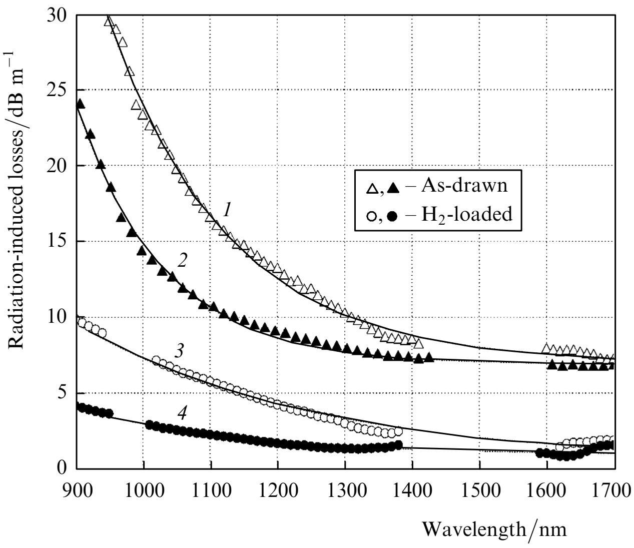

Figure 3. RIL in the as-drawn (*1*, *2*) and H_2-loaded fibre (*3*, *4*) measured in 1 day (*1*, *3*) and in 4 months (*2*, *4*) after the irradiation, respectively. The solid curves show approximations of the RIL by descending exponential functions.

As one would expect, the H_2-loaded fibre spectrum measured before irradiation demonstrates characteristic overlapping absorption bands of molecular hydrogen [15] (Fig. 2). However, this absorption is insignificant as compared to the RIL. By the amplitudes of the absorption bands at the wavelengths of 1080 and 1240 nm, the H_2 concentration in the H_2-loaded fibre glass can be estimated as $\sim 1\times10^{19}$ cm^{-3} [16]. One can also see that H_2-loading of the fibre glass allowed the RIL reduction by several times (Figs 2 and 3). Thus, as in the case of undoped-silica core fibres, in erbium fibre, hydrogen enters into the glass network and 'heals' radiation colour centres.

Within 4 months after irradiation, the RIL decreased in the both fibres (Fig. 3) due to thermal decay of radiation colour centres. As this took place, the thermal decay proceeded more quickly in the H_2-loaded fibre: its loss was 5 – 6 times less than in the as-drawn fibre. The increase in the decay rate of the H_2-loaded fibre could be due to supplementary diffusion of hydrogen from the cladding into the core. Note that the RIL measured within 4 months after the irradiation corresponds more closely to the RIL in space conditions, where the dose rate is many times smaller than in our experiment. It is interesting that the measurements performed within 8 months after the irradiation did not reveal further RIL decrease. This means that the decay of colour centres had virtually stopped, and the RIL level had stabilised.

Figure 4 shows the results of measurements of the differential lasing efficiency η performed within 4 months after irradiation. After irradiation by a dose of 2 kGy, differential lasing efficiency η of the H_2-loaded fibre decreased from 40 % to 32 %, whereas η for the as-drawn fibre decreased almost fivefold, and the lasing threshold increased by about 12 times. Thus, the as-drawn fibre became virtually inoperative.

Some extension of the erbium fibre service life in space can be achieved by pumping at $\lambda_p = 1480$ nm, where the

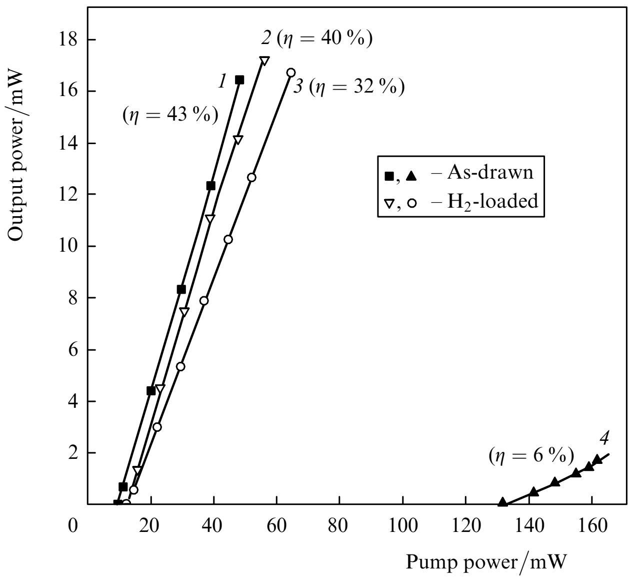

Figure 4. Dependences of the output power on the pump power ($\lambda_p = 980$ nm) for lasers based on the as-drawn (*1*, *4*) and H_2-loaded (*2*, *3*) fibres before (*1*, *2*) and 4 months after (*4*, *3*) their irradiation, respectively.

RIL is noticeably smaller than that at $\lambda_p = 980$ nm (see Figs 2 and 3). However, pumping at 1480 nm gives a much lesser effect than H_2-loading of an erbium fibre.

The reduction of the lasing efficiency of the laser shown schematically in Fig. 1, can be estimated by calculating the signal and pump power absorbed in the cavity. In this case, we assume that at a small irradiation dose (and therefore a small radiation-induced loss), the output power and the distribution of the signal and the pump along the cavity vary weakly. In addition, we assume that the pump power distribution along the fibre length is close to an exponential one.

The differential lasing efficiency obtained under the above assumptions is described by the expresion:

$$\eta = \eta_0(1 - C_p\alpha_{\text{RIA p}})(1 - C_s\alpha_{\text{RIA s}}), \tag{1}$$

where η_0 is the differential lasing efficiency measured before the irradiation; $\alpha_{\text{RIA p}}$ and $\alpha_{\text{RIA s}}$ are the radiation-induced optical absorption at the pump and signal wavelengths, respectively; C_s and C_p are constants defined by expressions

$$C_s = \left[\frac{\ln 10}{5}\frac{L}{\ln(1/R)}\right], \tag{2}$$

$$C_p = \left\{\frac{1}{\gamma\alpha_p}\left[1 - \exp\left(-\frac{\ln 10}{10}\gamma\alpha_p L\right)\right]\right\}. \tag{3}$$

Here L is the laser cavity length; $R = 4$ % is the coefficient of reflection of the signal power from the perpendicular fibre cleavage; α_p is the pump absorption in the presence of a small signal in the fibre before the irradiation; and γ is a coefficient measured experimentally, which takes into account the decrease in the pump absorption rate due to fibre bleaching upon high-power pumping.

With a pump at $\lambda_p = 980$ nm, the optimal cavity length $L = 1.2$ m, and $\gamma = 0.65$, we obtained $C_s \approx 0.17$ and $C_p \approx 0.1$. Because the pump absorption at 980 and 1480 nm is approximately the same [see curve (*1*) in Fig. 1], for $\lambda_p = 1480$ nm one may use the same L and γ and consequently the same C_s and C_p as those determined for $\lambda_p = 980$ nm. Note that the lasing efficiency is almost two times more sensitive to the optical loss at the wavelength of 1550 nm, because in our experimental scheme the signal radiation traverses a two times longer path than the pump radiation.

Because of our assumptions, at a high RIL level, the efficiency calculated by (1) differs considerably from the measured one. For example, for an optical loss corresponding to curve (*4*) of Fig. 2, the calculations give a η reduction to 23 %, whereas the measured efficiency is 32 %. Nevertheless, expression (1) allows one to determine approximately the characteristic radiation dose at which the lasing efficiency starts to decrease.

Estimations show that the output power of a laser based on an H_2-loaded erbium fibre pumped at 980 nm will decrease by 10 % at a radiation dose of 0.4 kGy, which corresponds approximately to two years' service of the fibre in space. Let us emphasise once again that this estimate gives the characteristic dose and time at which the lasing efficiency just starts to go down, whereas for a 5 times longer service time (10 years) the fibre still remains serviceable (the measured lasing efficiency decreases just from 41 % to 32 %). For comparison, for an H_2-free fibre the corresponding characteristic dose is just 63 Gy, which corresponds to 4.5 months of service in space.

To determine the fibre service life at $\lambda_p = 1480$ nm, it is necessary to introduce new γ and α_p values and a different value of optimal fibre length L. However, because for the fibre under study the difference of the α_p values at the wavelengths of 980 and 1480 nm is not large (about 10 %), one may use the former L and γ values in the calculations.

According to our estimates, upon pumping at $\lambda_p =$ 1480 nm, a 10 % reduction of the fibre laser power will occur in 6.5 months of space operation, which corresponds to an irradiation dose of 107 Gy. In other words, as compared to the case of pumping at $\lambda_p = 980$ nm, the service life will increase by a factor of just 1.5. Such a small difference is due to a larger contribution of the optical loss at 1530 nm to the decrease in the lasing efficiency. The H_2-loading prolongs the fibre service life by about 6 times, up to 3.5 years (the dose of 0.7 kGy), as well as in the case of pumping at $\lambda_p = 980$ nm.

The results of the estimates of the differential lasing efficiency upon pumping at $\lambda_p = 980$ and 1480 nm are given in Table 1.

Table 1.

Fibre	H_2-loading	Radiation dose at which η decreases by 10 % (in parenthesis an estimated lifetime of the fibre in space corresponding to this dose is indicated)	
		$\lambda_p = 980$ nm	$\lambda_p = 1480$ nm
As-drawn	–	63 Gy (4.5 months)	107 Gy (6.5 months)
H_2-loaded	for $P = 5$ MPa	0.4 kGy (2 years)	0.7 kGy (3.5 years)

The calculations and the experiments show that hydrogen loading of a fibre with a hermetic coating, preventing H_2 backdiffusion from the glass, allows many-fold extension of the erbium fibre service life in the space conditions.

The demonstrated magnitude of the radiation-hardening effect of erbium fibre is not apparently limiting. An additional enhancement of radiation resistance can be obtained by increasing somewhat the H_2 concentration, which should not result, at the same time, in strong absorption by molecular hydrogen. It appears to be also of interest to use molecular deuterium instead of hydrogen. The D_2 absorption bands are shifted to the red with respect to the H_2 bands, which may turn out to be useful.

4. Conclusions

It has been shown that H_2-loading of an erbium fibre reduces radiation-induced light absorption in the near-IR region by several times. The differential lasing efficiency of an H_2-loaded fibre decreases after gamma-irradiation to a dose of 2 kGy only slightly, whereas an H_2-free fibre virtually loses its lasing capacity. Numerical estimates have shown that H_2-loading allows prolongation of the service life of active fibres in space approximately by a factor of 6.

An essential gain in radiation resistance, which we have demonstrated for an H_2-containing hermetically coated erbium fibre, testifies that such fibres hold much promise for space applications.

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